Spectroscopic EUV reflectometry for characterization of thin film systems and determination of optical constants

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EXTATIC

EUV Experimental Physics of Extreme Ultraviolet

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Motivation

Why EUV reflectometry?

Innovative surface sensitive metrology with EUV radiation

alternative to existing
(non-destructive) metrology tools

Potential:

- ultra-thin film analysis (any material)
- determination of chemical bonds at surfaces
  (near edge absorption fine structure)
- surface sensitive technique (penetration depth ~ 10-100 nm)
- surface roughness determination
  (smooth surface limit beyond VIS or UV)
- high spatial resolution (<< 1 µm)
- defect inspection („nano“roughness in terms of spatial-frequency)

need for „at wavelength“
characterization of EUV optics

- at synchrotron reflectometers
- laboratory based reflectometers

Long-term goal:
transfer techniques into the lab

simultaneous acquisition from one measurement

➢ **experimental determination of EUV optical constants**

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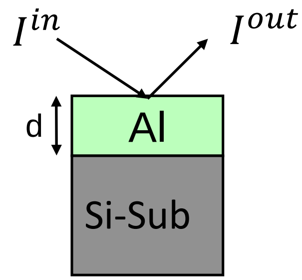
Angle-resolved vs. spectral reflectometry

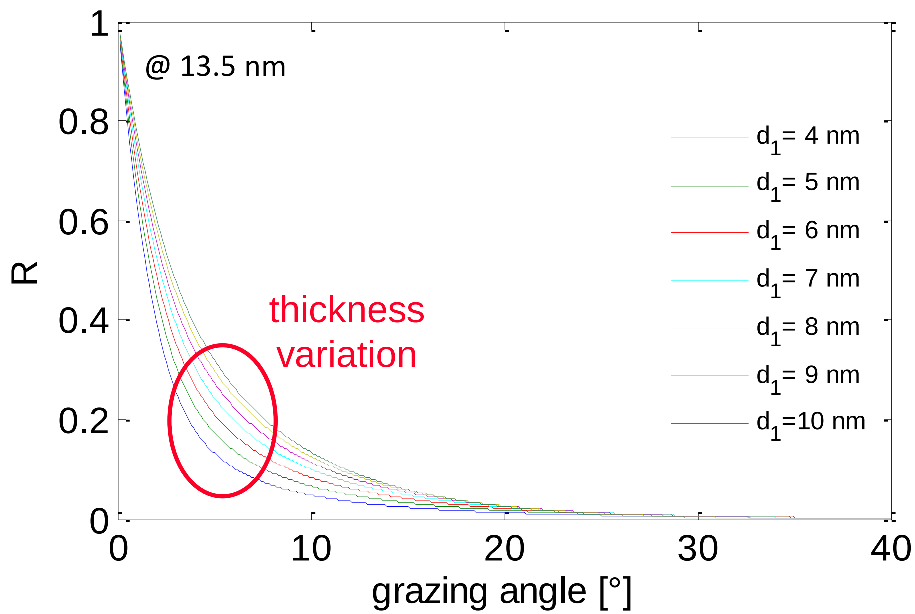
Layer parameters determination:

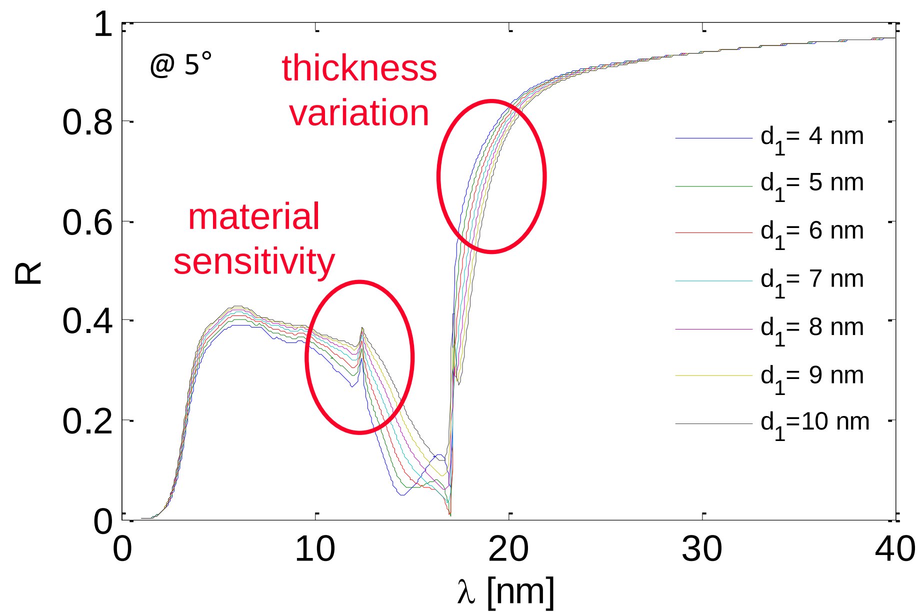
(by fitting experimental data with a model)

- Thickness
- Density
- Roughness



$$R(\theta,\lambda) = I^{out}/I^{in}$$





- ➢ **Absorption edges: elemental & chemical sensitivity**
- ➢ **Total external reflection at high critical angles (up to 10º – 20º)**

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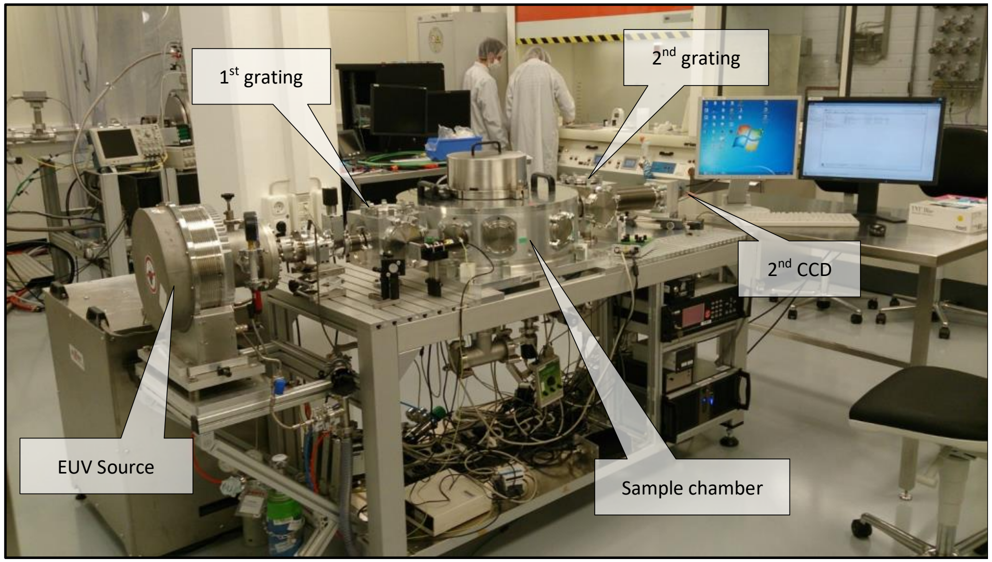
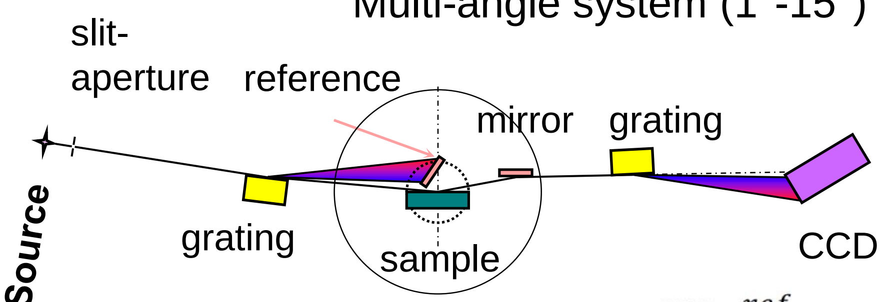
Polychromatic Angle-resolving Non-destructive Tool for High-speed Extreme-ultraviolet Reflectometry – PANTHER

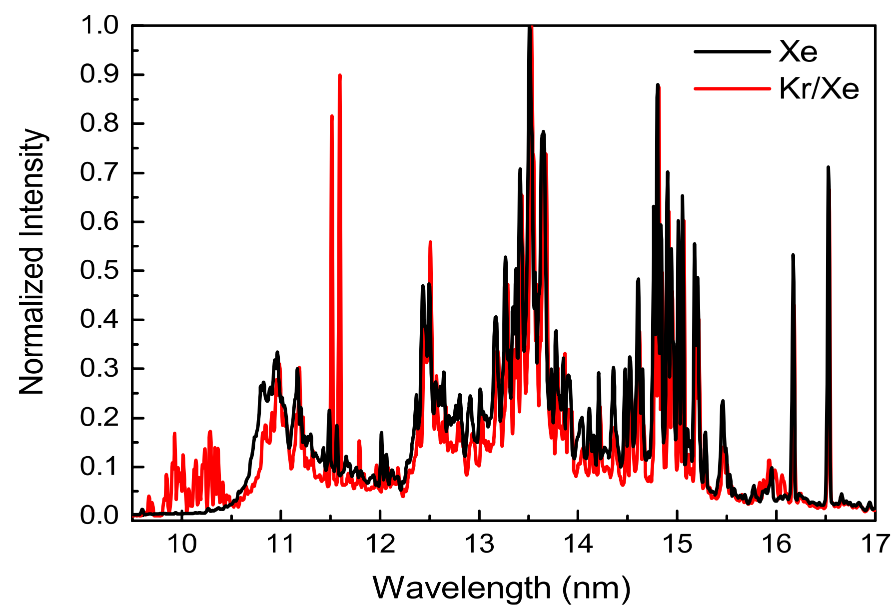


- Wavelength range: 9 - 17 nm
- Spectral resolution: 5 pm
- Incidence angles: 1 - 15°
- Angular resolution: 0.005°
- Pulse-to-pulse measurements
- Pulse duration: 10 - 100 ns
- Thickness sensitivity: ~0.1 nm
- Sample size <100 mm

Multi-angle system (1°-15°)



$$R(\theta,\lambda) = \frac{I_2^{sam}}{I_1^{sam}} \frac{I_1^{ref}}{I_2^{ref}} R^{ref}$$



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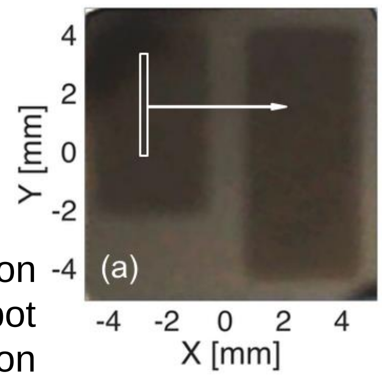
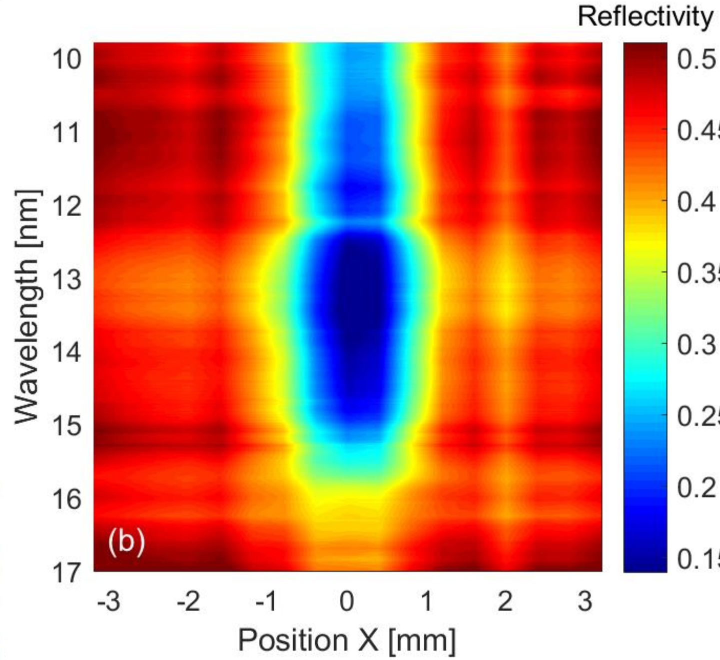
Spatially resolved spectroscopic EUV reflectometry

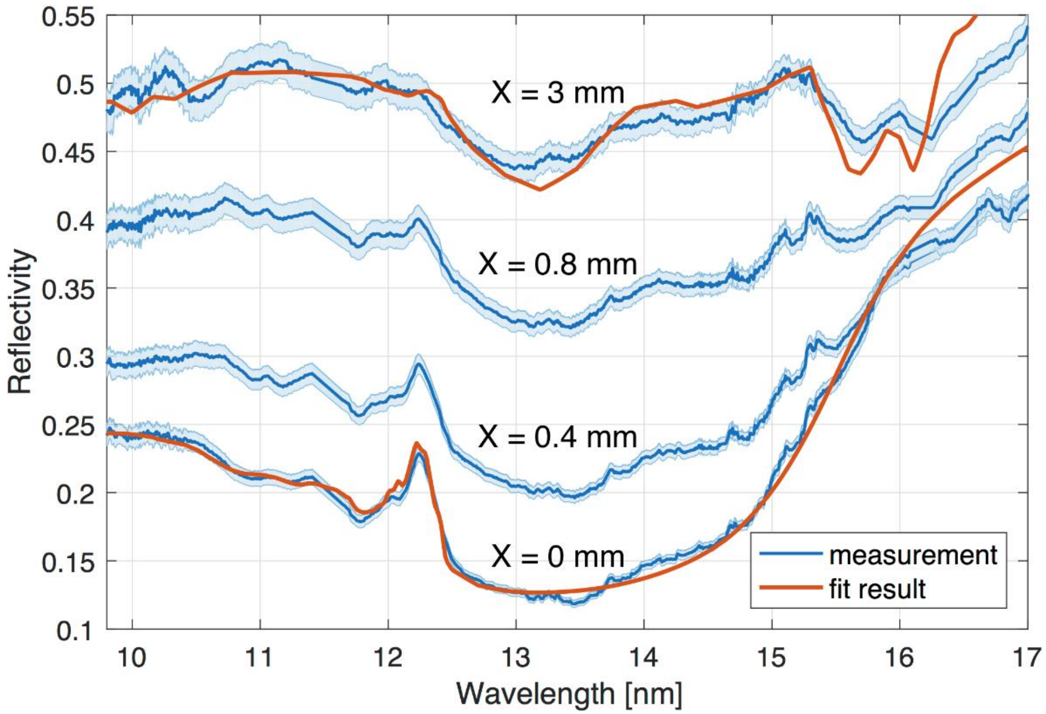
Application example:
study of collector optics contamination due its proximity to EUV source



Si sample with contamination regions with marked EUV spot footprint and scan direction



Resulting spectral reflectivity map

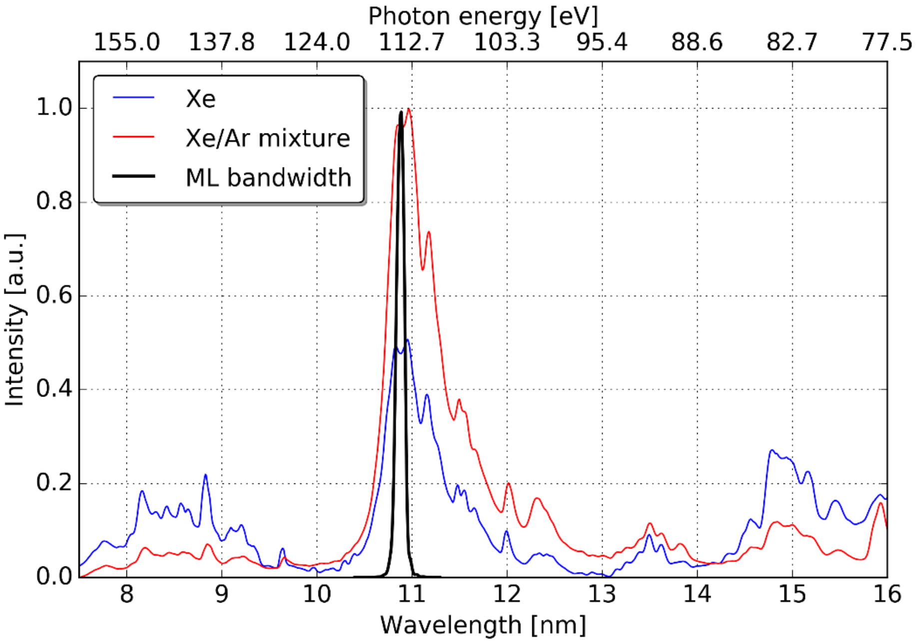


Reflectivity spectra (blue) & fit results (red) at different sample positions

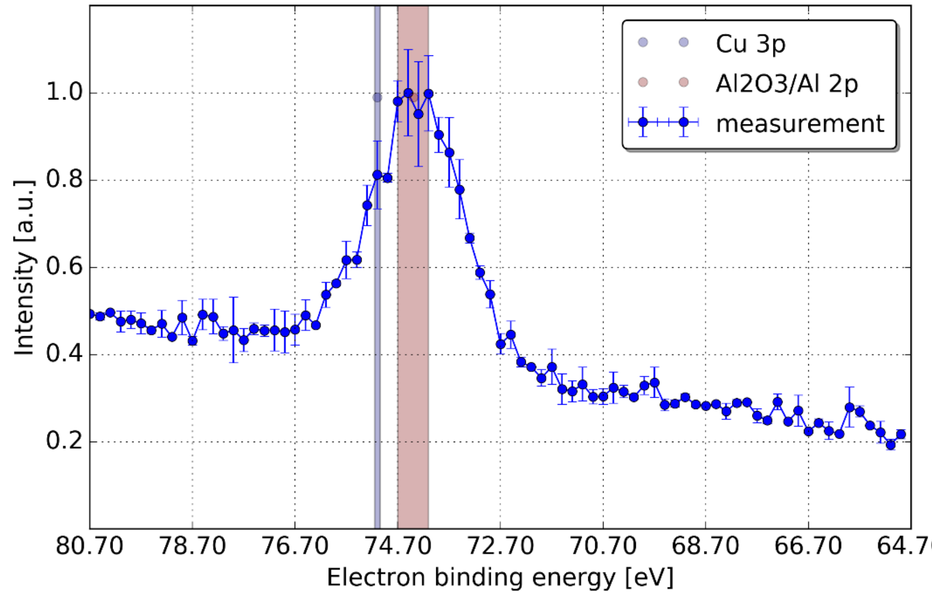
Non-contaminated part (X = 0 mm) shows presence of natural silicon oxide layer (4 nm) and non-uniform rough layer of carbon (2.5 nm) on top.

Contaminated region (X = 3 mm) has 0.7 nm carbon and 10 nm amorphous Al_2O_3 topping oxidized silicon wafer.

Cross-correlation with photoemission electron microscopy (PEEM)



EUV emission spectra utilized for PEEM: λ = 10.9 nm (E_{photon} = 113.7 eV) was filtered by two narrow-bandwidth multilayer mirrors with $\Delta\lambda$ = 0.1 nm



Section of photoelectron spectrum measured at 113.7 eV photon energy with highlighted electron binding energies of materials that fit within the peak

- From PEEM results, one cannot clearly distinguish between oxidized aluminum and copper
- EUV reflectometry clearly shows presence of aluminum oxide, ruling out the copper content, which also fits to the sample history
- Carbon contamination could not be tested with PEEM, as used photon energy of 113.7 eV was lower than the electron binding energy of the carbon K-shell

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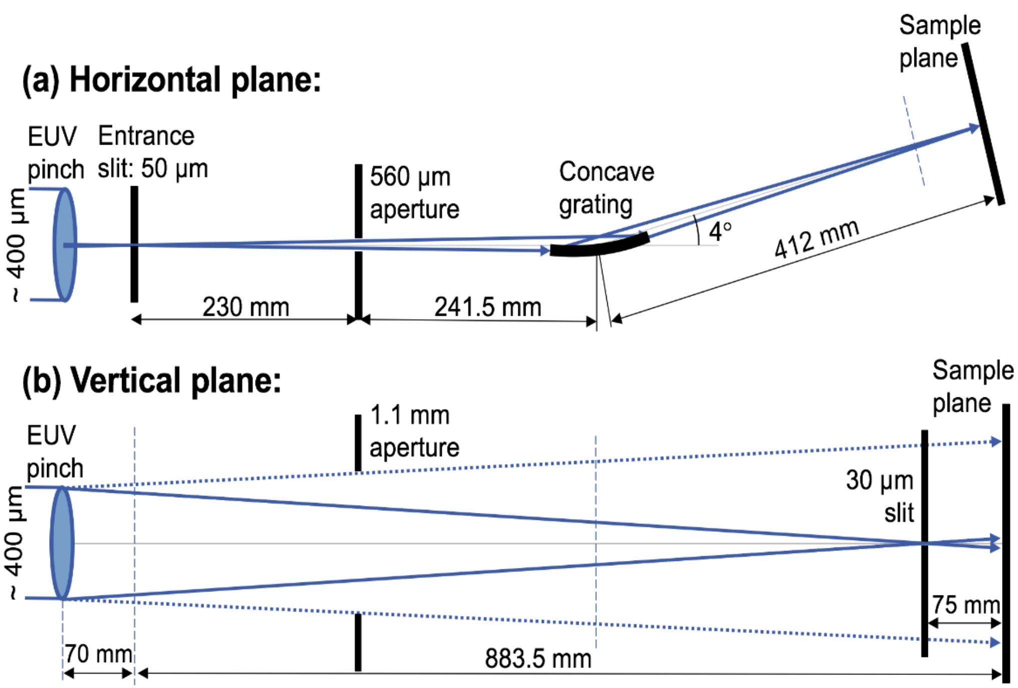
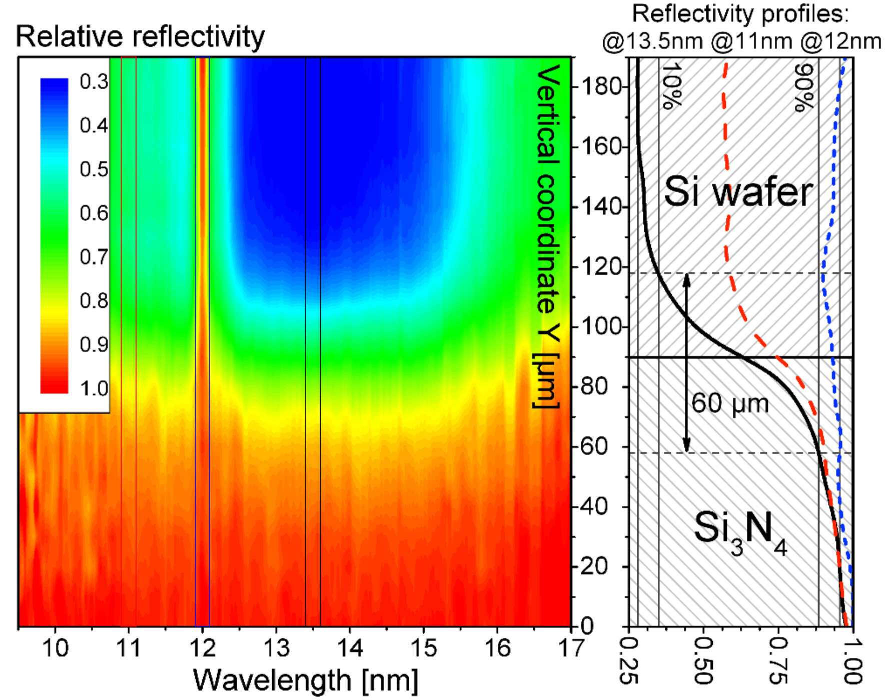
Spatial resolution of the PANTHER

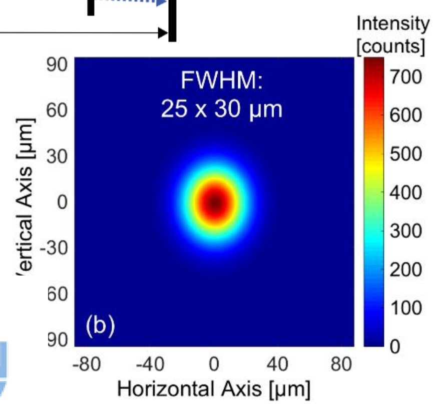
Sample illumination scheme of reflectometer with 30 µm slit in front of sample plane (dotted line: beam path without this slit)





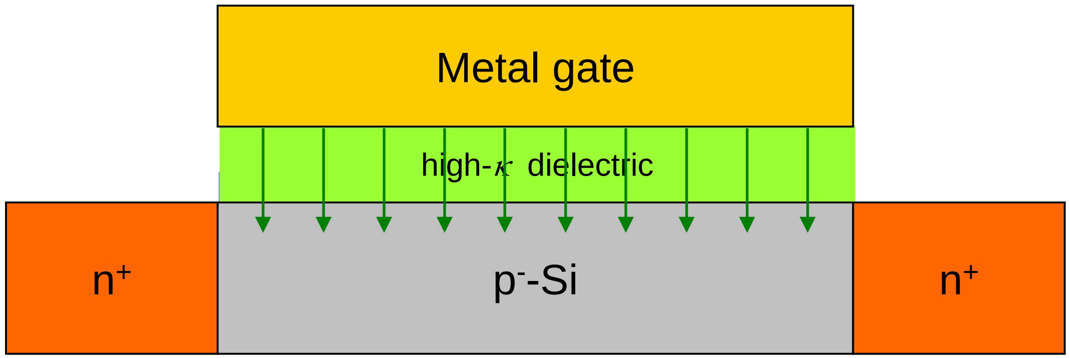
Ultimate illumination spot size (at sample: 25 µm/sinθ x 30 µm)

For smaller spots imaging optics needed



Relative reflectivity scan at 8° grazing incidence across an abrupt horizontal Si/Si_3N_4 field border with vertical sample movement; reflectivity profiles at 11, 12, and 13.5 nm; knife-edge resolution test at 13.5 nm

Application example: high-κ dielectrics



$$C = \kappa \frac{\varepsilon_0 A}{d}$$

C: capacitance

A: area of capacitor

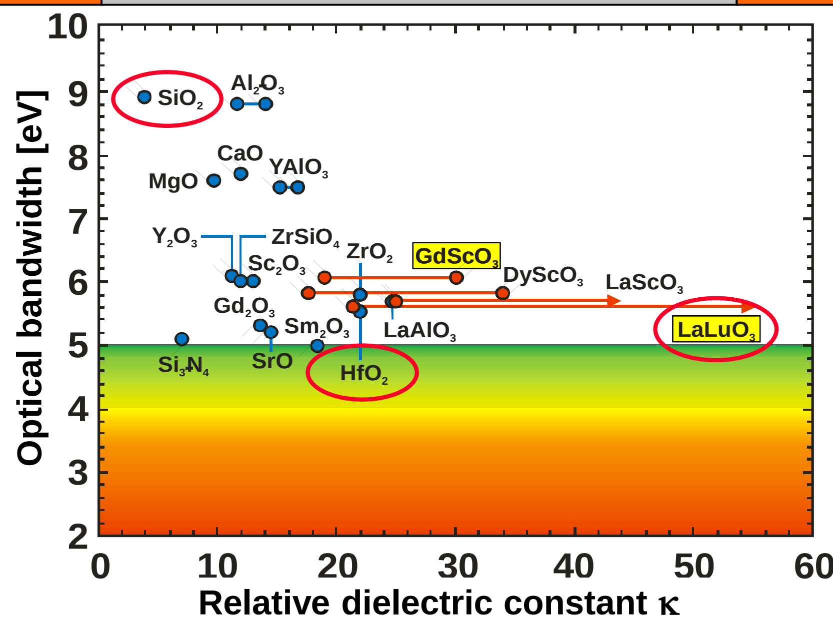
d: thickness of insulator

ε_0: permittivity of free space

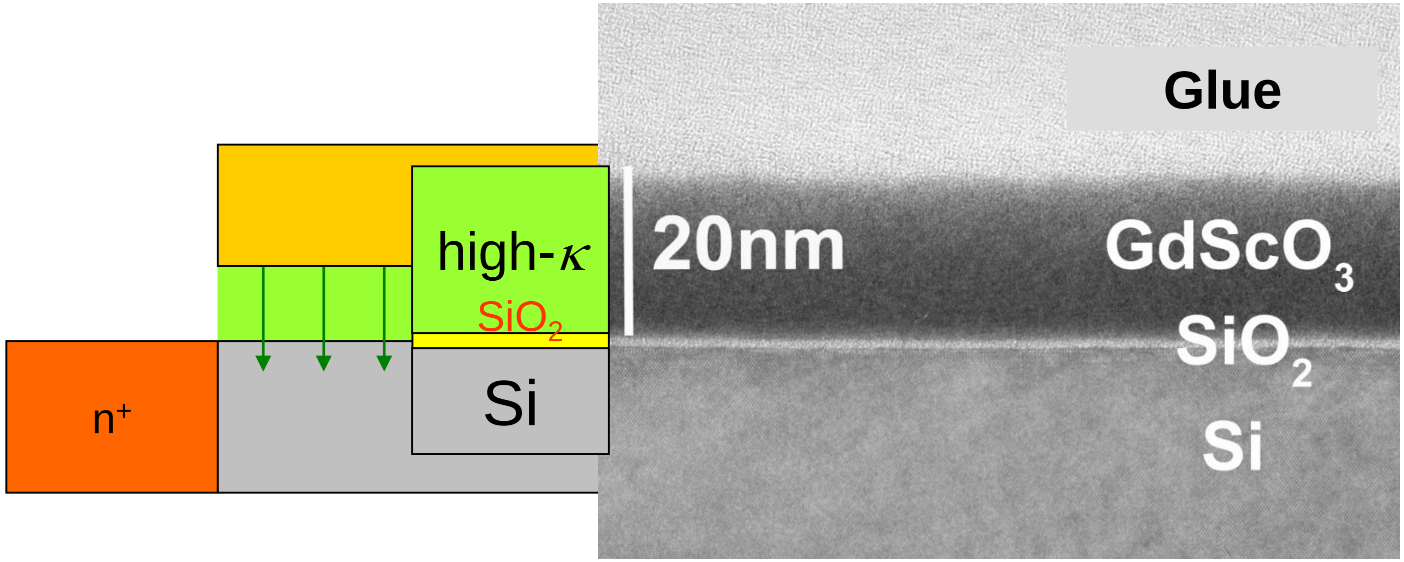
κ: rel. dielectric constant

E: electric field

J: tunneling/leakage current



„Parasitic“ interface

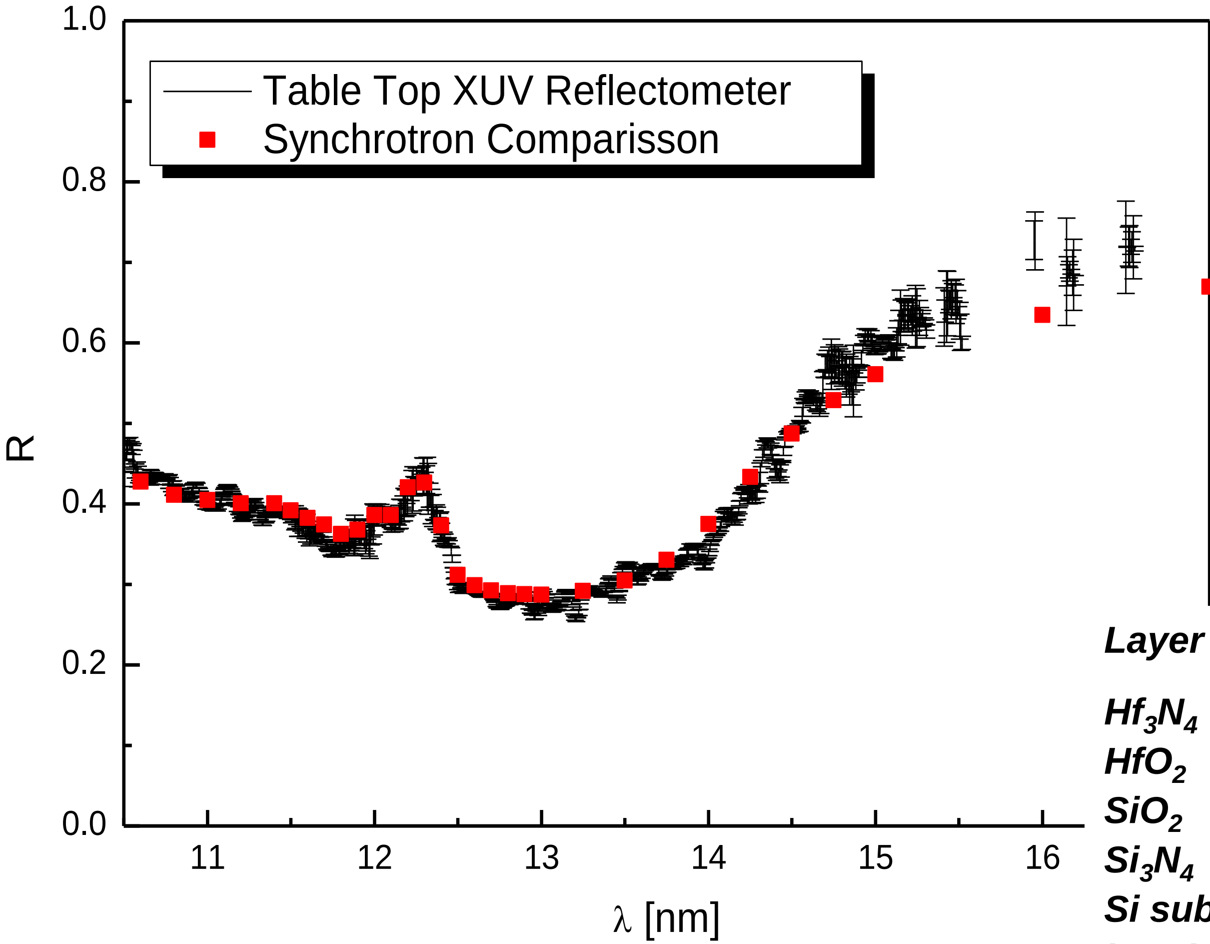


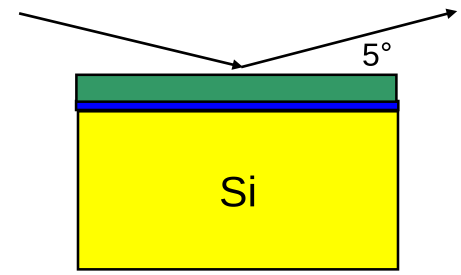
SiO_2-Interface of high quality:

- decreases interface-states drastically
- increases charge carrier mobility in silicon
- decreases leakage currect

Application example: characterization of high-k layers

Determination of ultra thin HfO_2 layers and buried oxide

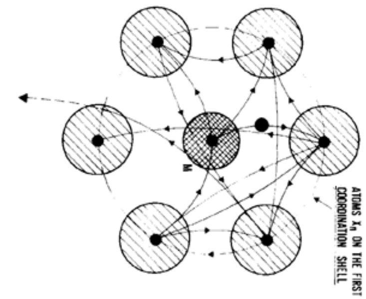




Layer Model:

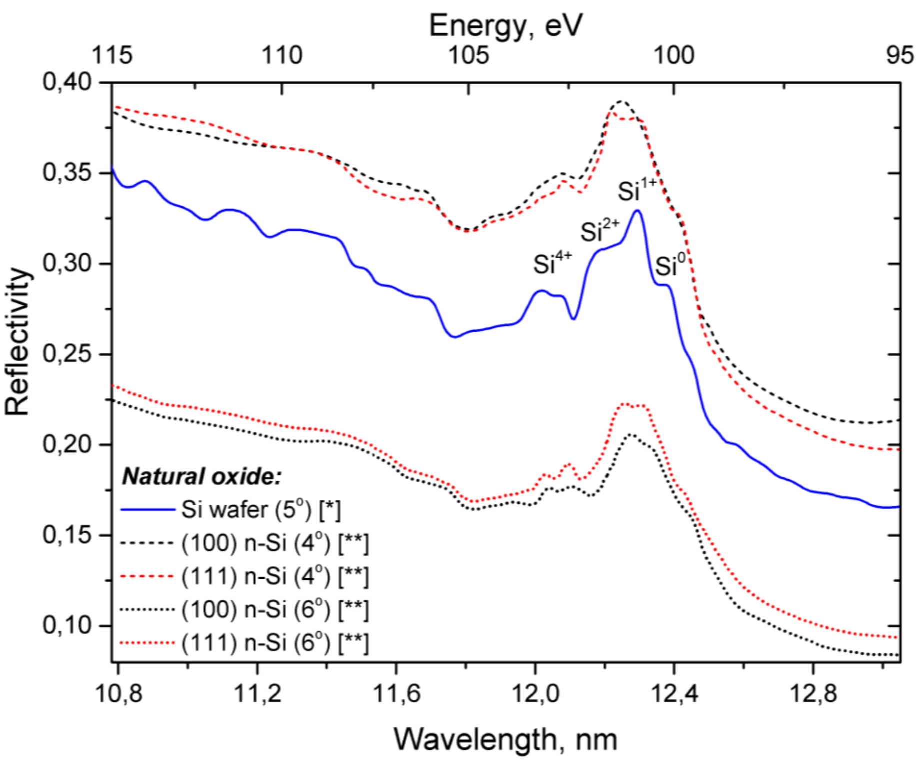
Hf_3N_4 d: 0.51 nm, density: 12.2 g/cm^3
HfO_2 d: 0.97 nm, density: 9.4 g/cm^3
SiO_2 d: 1.00 nm, density: 2.4 g/cm^3
Si_3N_4 d: 0.83 nm, density: 4.1 g/cm^3
Si substrate
interlayer roughness/diffusion: 0.33 nm

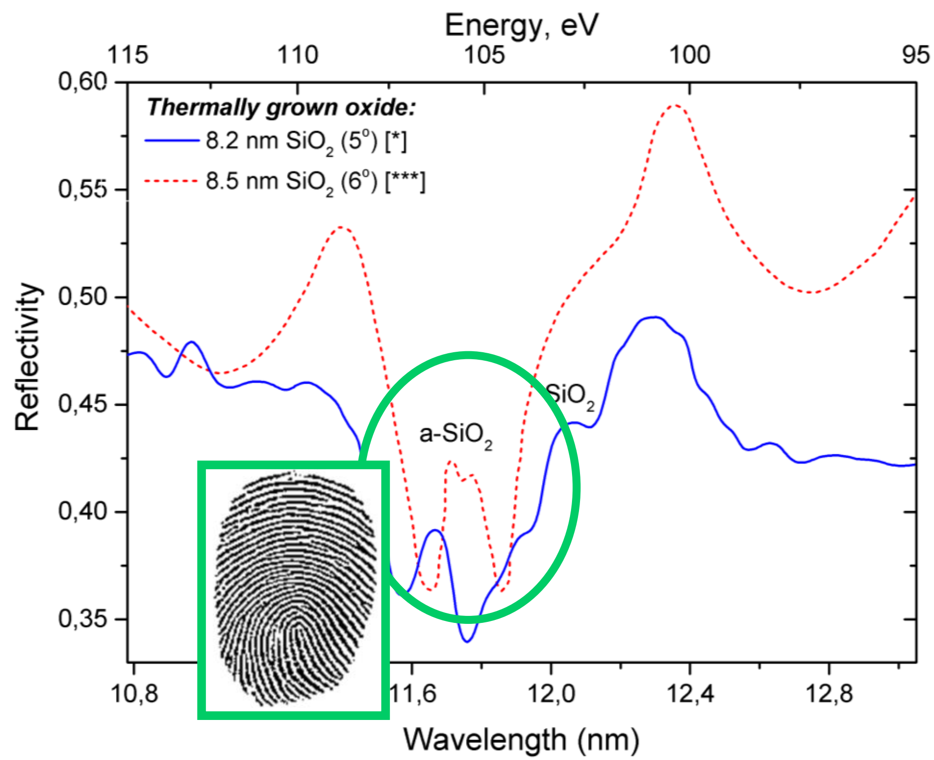
Near-edge EUV reflectometry



Near-Edge X-Ray Absorption Fine Structure (NEXAFS)

- Determination of chemical bonds and local symmetry
- Quick qualitative interpretation (fingerprinting)





[*] M. Banyay, PhD thesis, RWTH Aachen (2011)
[**] E. O. Filatova, et al., Tech. Phys. Lett. **35** (1), 70-72 (2009)
[***] E. O. Filatova, et al., Phys. Solid State **40** (7), 1237-1240 (1998)

database built-up needed („fingerprint-concept“)

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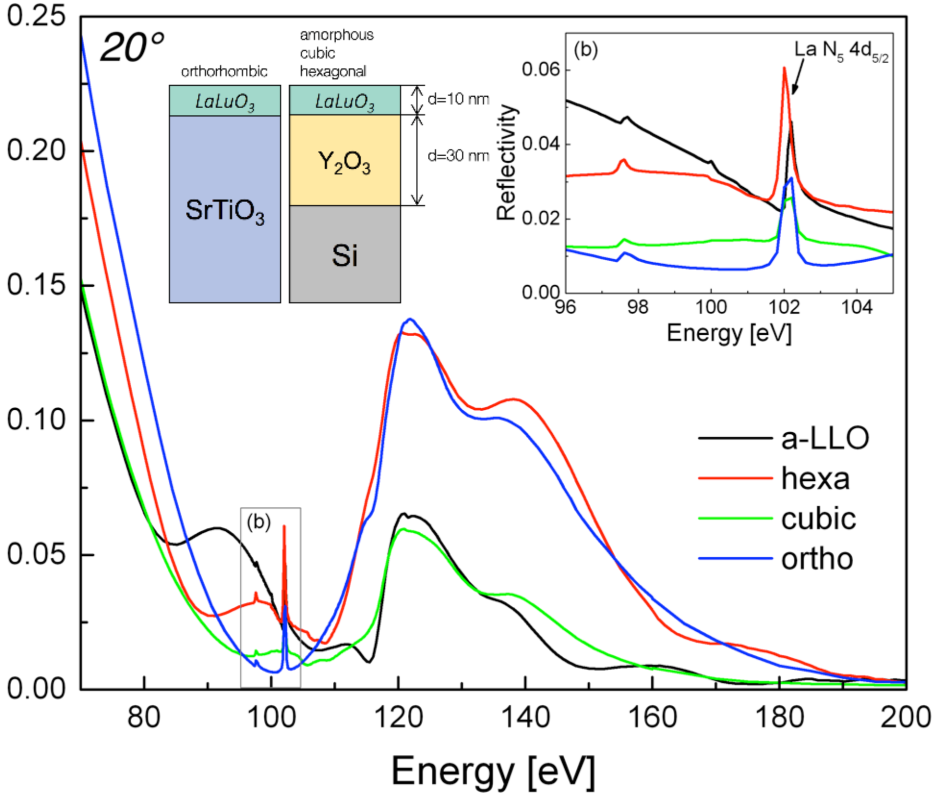
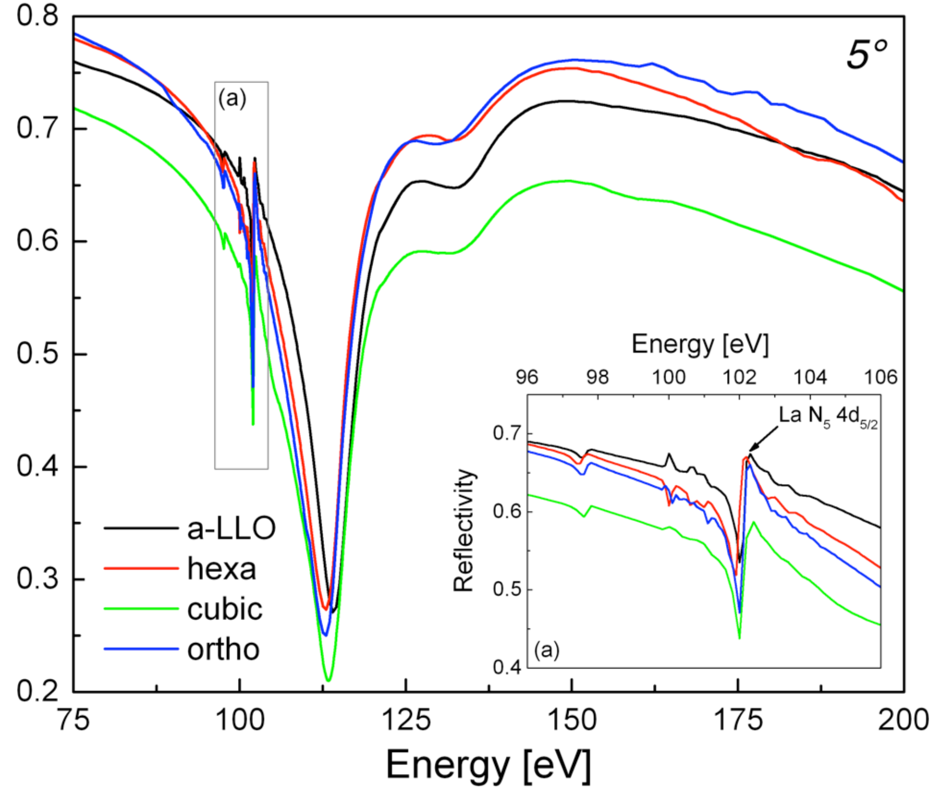
$LaLuO_3$ (LLO) layers of different crystallinity

- **LLO – high-k material, promising as a gate dielectric (SiO_2, HfO_2 replacement)**
- **Four crystalline modifications of LLO have been investigated**
- **Untabulated near-edge features and La N-edge shift observed**

Reflectivity at 20° grazing incidence



Reflectivity at 5° grazing incidence



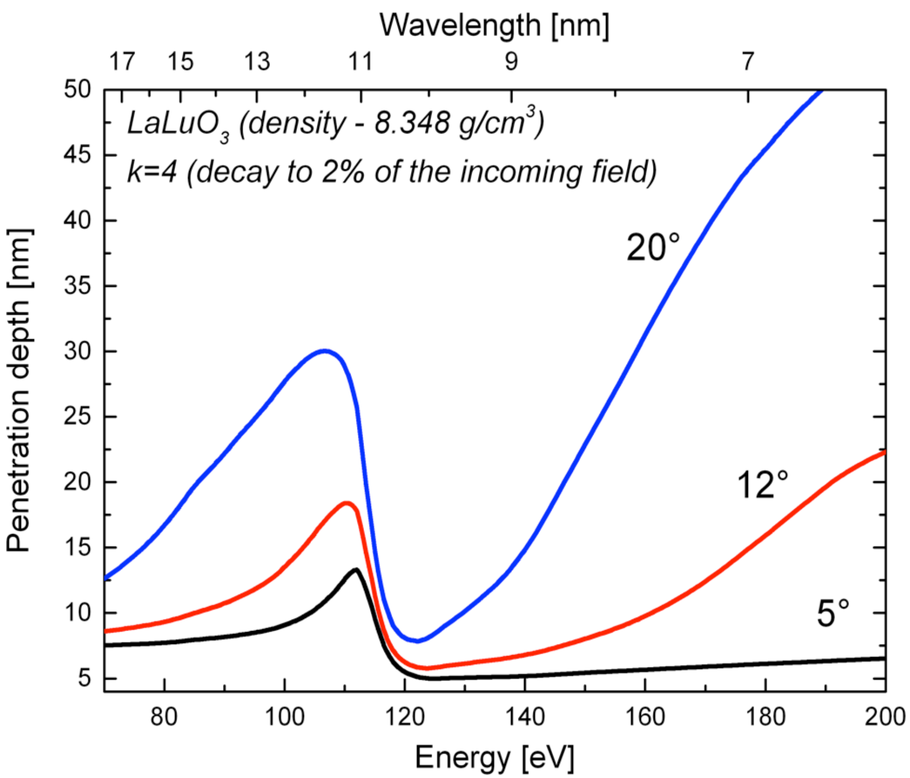
Reflectivity measurements from BEAR beamline of ELETTRA synchrotron, Trieste

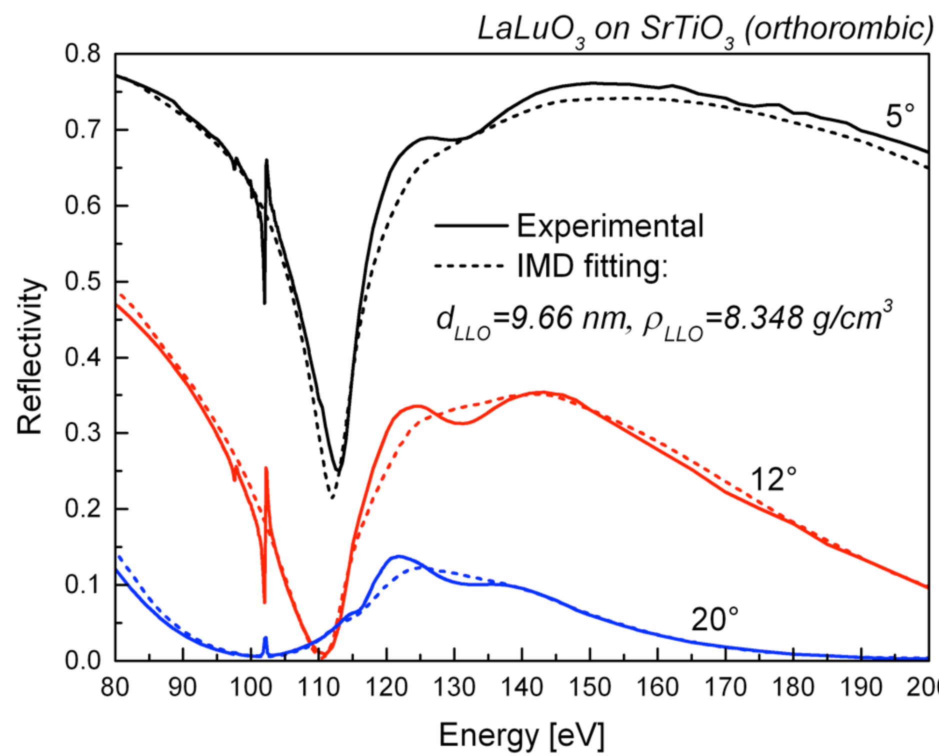
$LaLuO_3$ (LLO) layers of different crystallinity

Penetration depth of EUV radiation into the interface (angle-dependent):

$$z_0^2 = k\frac{\lambda^2}{8\pi^2\beta^2}\left(\sqrt{(\theta^2-2\delta)^2+4\beta^2}+\left(\theta^2-2\delta\right)\right),\ where\ n = 1-\delta+i\beta$$

Penetration depth and fitting results





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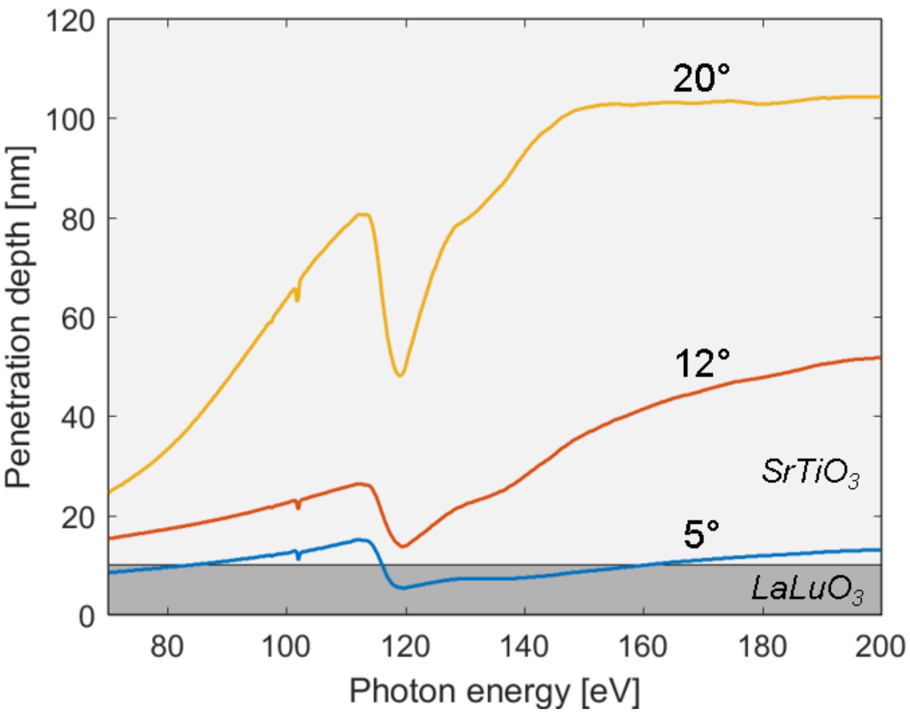

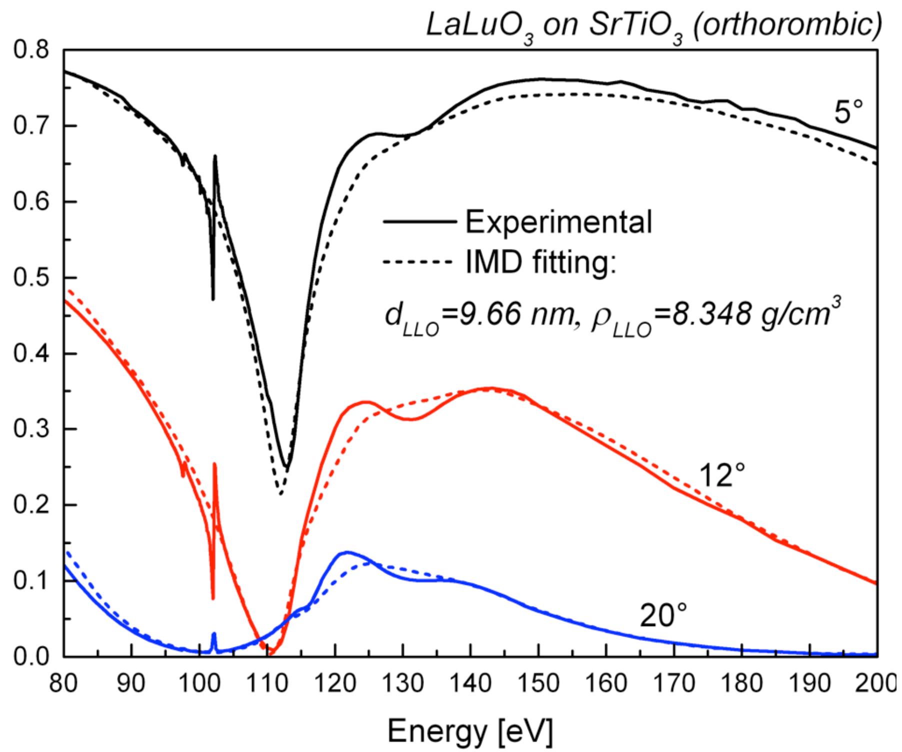

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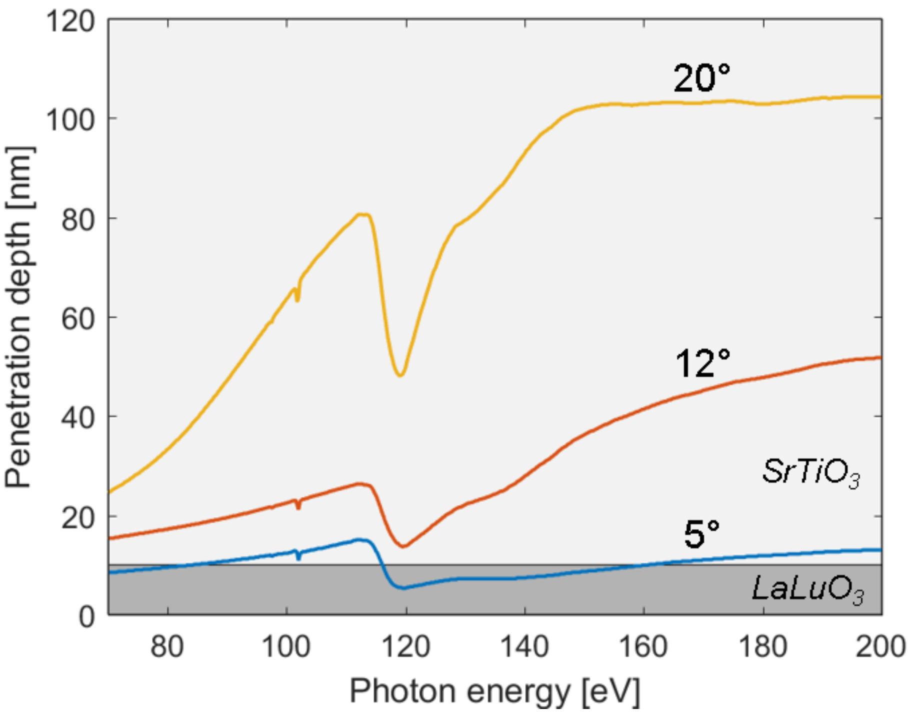

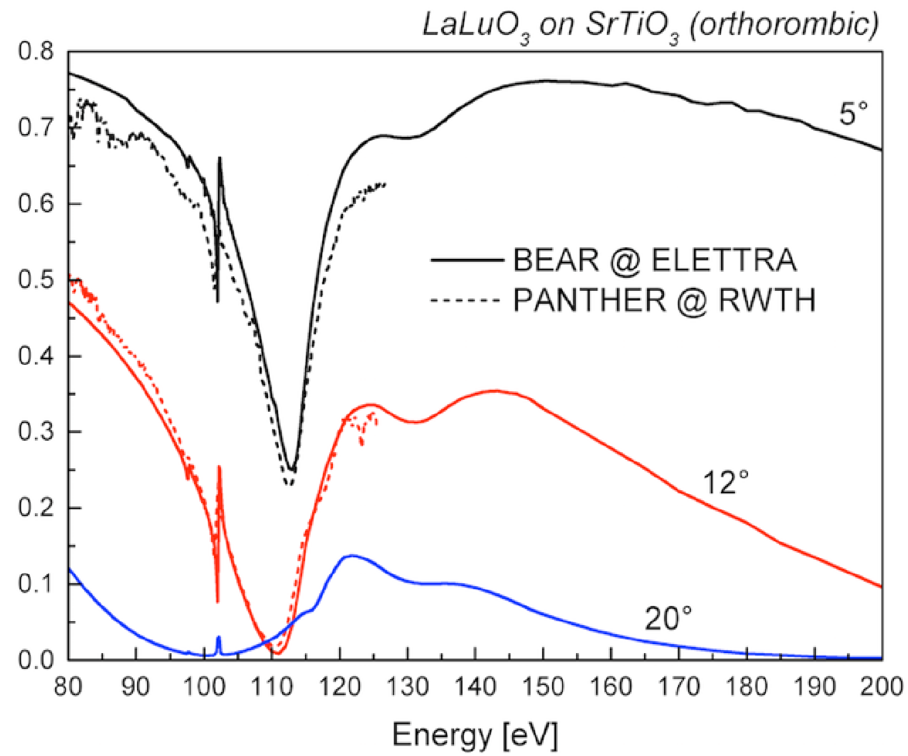

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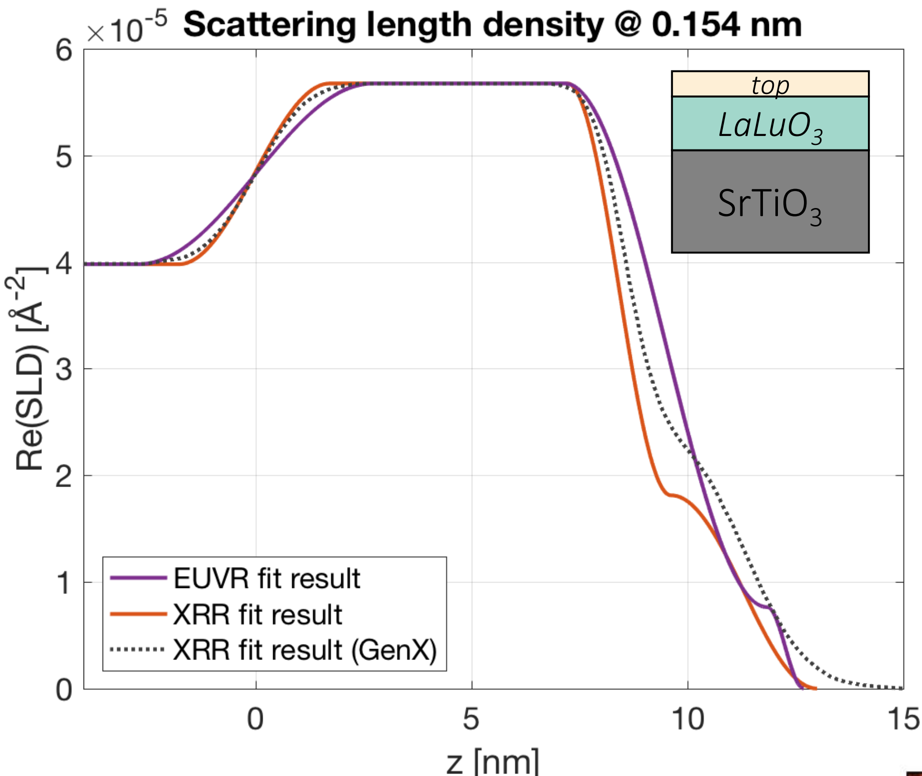
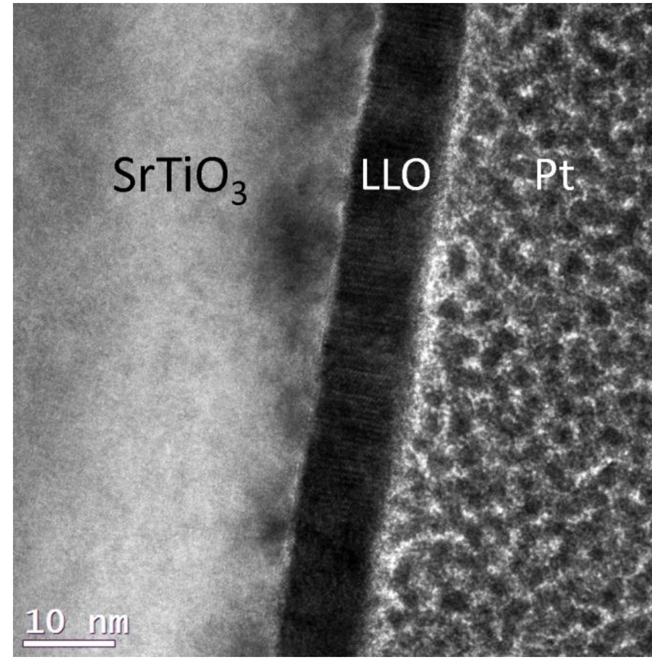
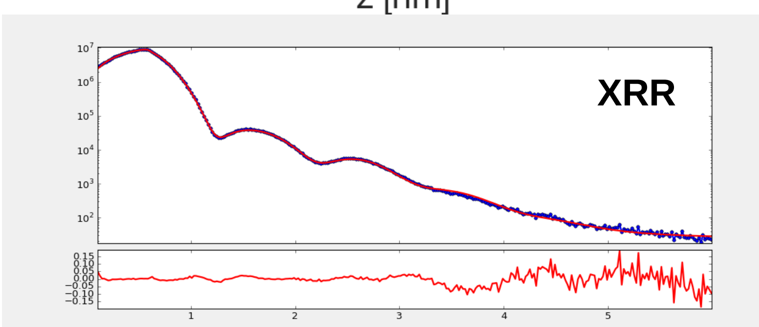
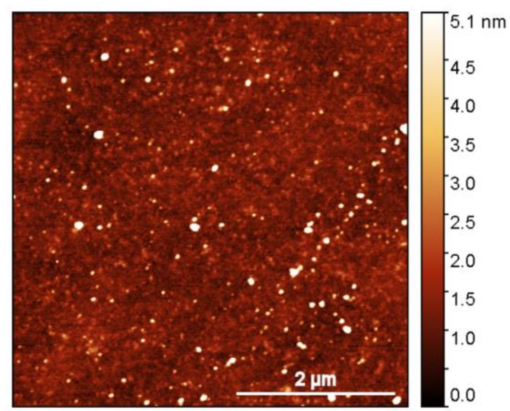
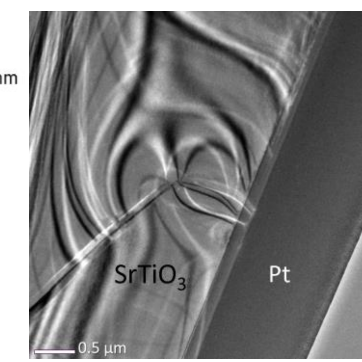
10 nm ortho-LLO #10742: SLD (δ) profiles, AFM / TEM images











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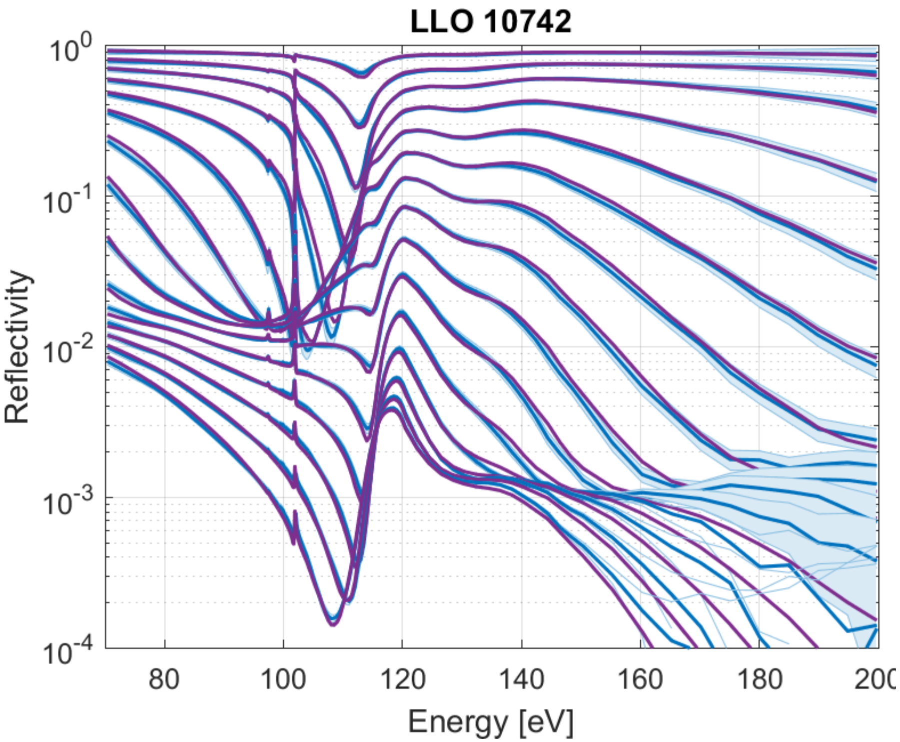
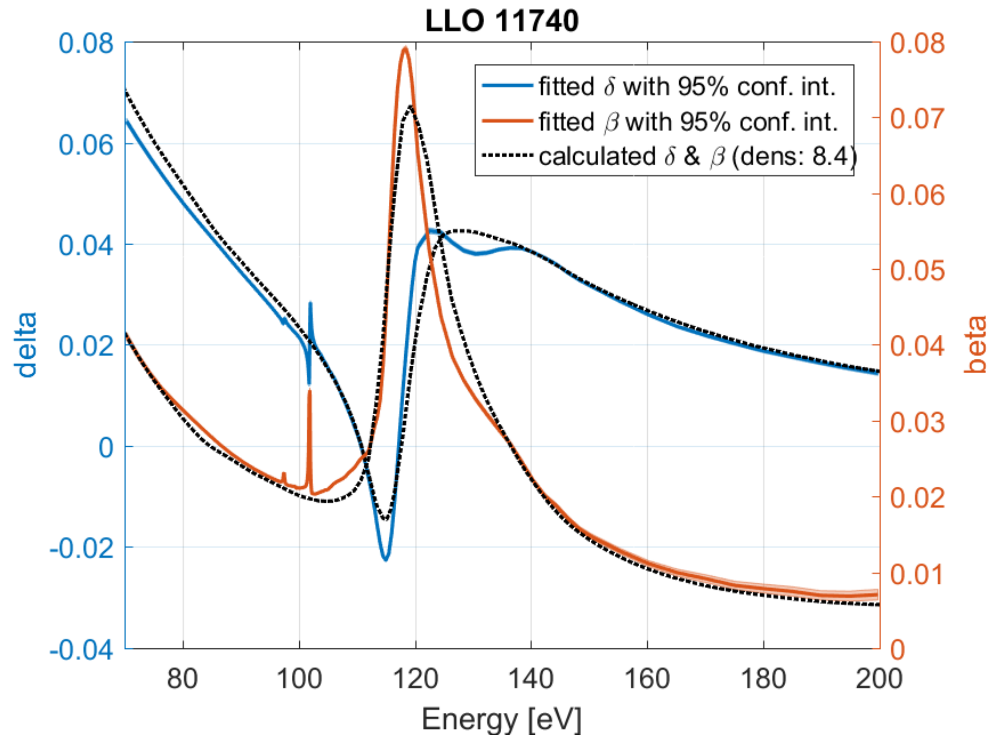
Refractive index obtained from reflectance data: orthorhombic LLO





10 nm ortho-LLO #10742: EUV only fit / n&k + structure fit

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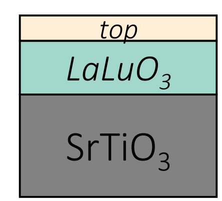
STR.shape = 'cos'
```

thick	rough	dens	La	Lu	O	Sr	Ti	C
0	**0.8520**	**0.8984**	0	0	0	0	0	1.0
4.4434	**4.6821**	8.4000	1.0	1.0	3.0	0	0	0
0	**5.4500**	5.1200	0	0	3.0	1.0	1.0	0



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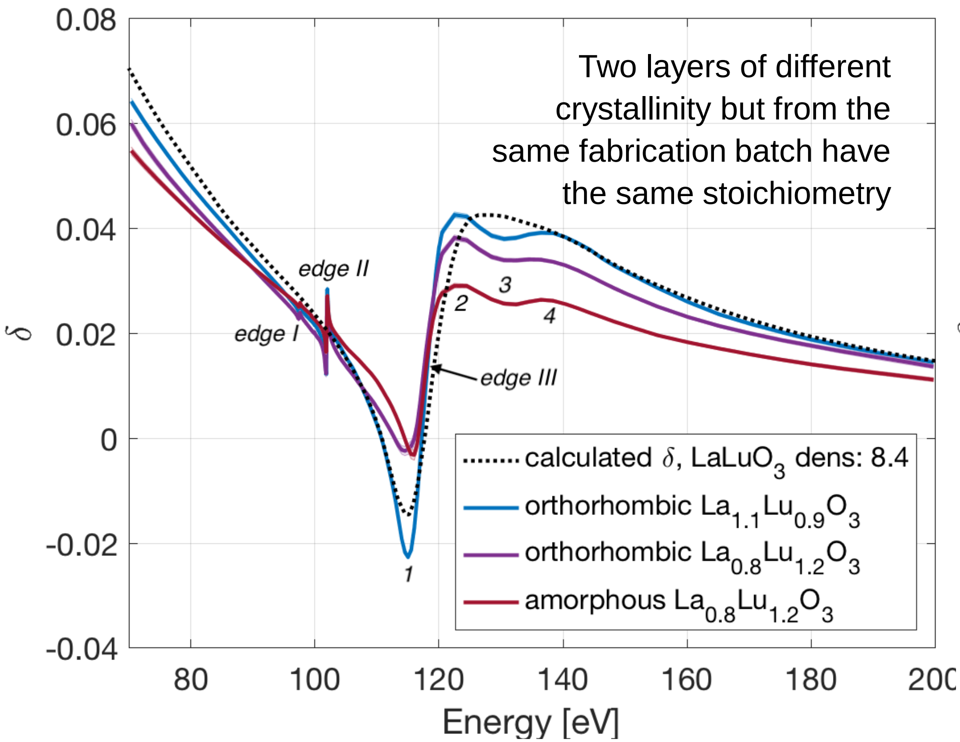
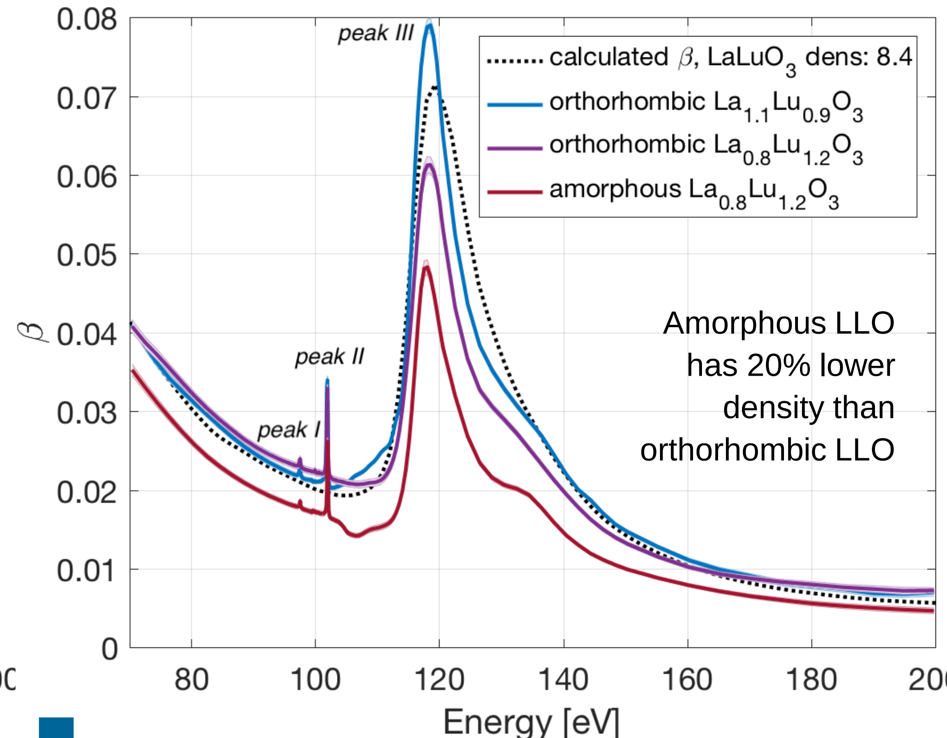
Comparison of LLO optical constants





EUV reflectometry:

- Experimental determination of EUV optical constants of materials of interest
- Characteristic absorption edge features and near-edge oscillations
  - Amplitude directly connected to element content in compound
  - Determination of density and stoichiometry by comparing to calculations
- Responsive quality control method due to high sensitivity to chemical composition

Summary

- EUV spectroscopic reflectometry is a powerful tool for analysis of thin films and film stacks with high surface/material sensitivity
  - non-destructive analysis of ultra-thin films
  - strong element selectivity
  - determination of chemical bonds (NEXAFS)
  - surface sensitive technique (up to ~100 nm)
  - surface roughness determination
  - potential for sub-µm spatial resolution
  - simultaneous acquisition from one measurement
- Laboratory EUV light for future metrology tools with high spatial resolution and throughput capability
- Pulse to pulse analysis allows to be independent on source fluctuations
- Multi-angle measurements allow to increase precision and stability
  - experimental determination of EUV optical constants
  - determination of layer density and stoichiometry
- Responsive quality control method due to high sensitivity to chemical composition and sample structure

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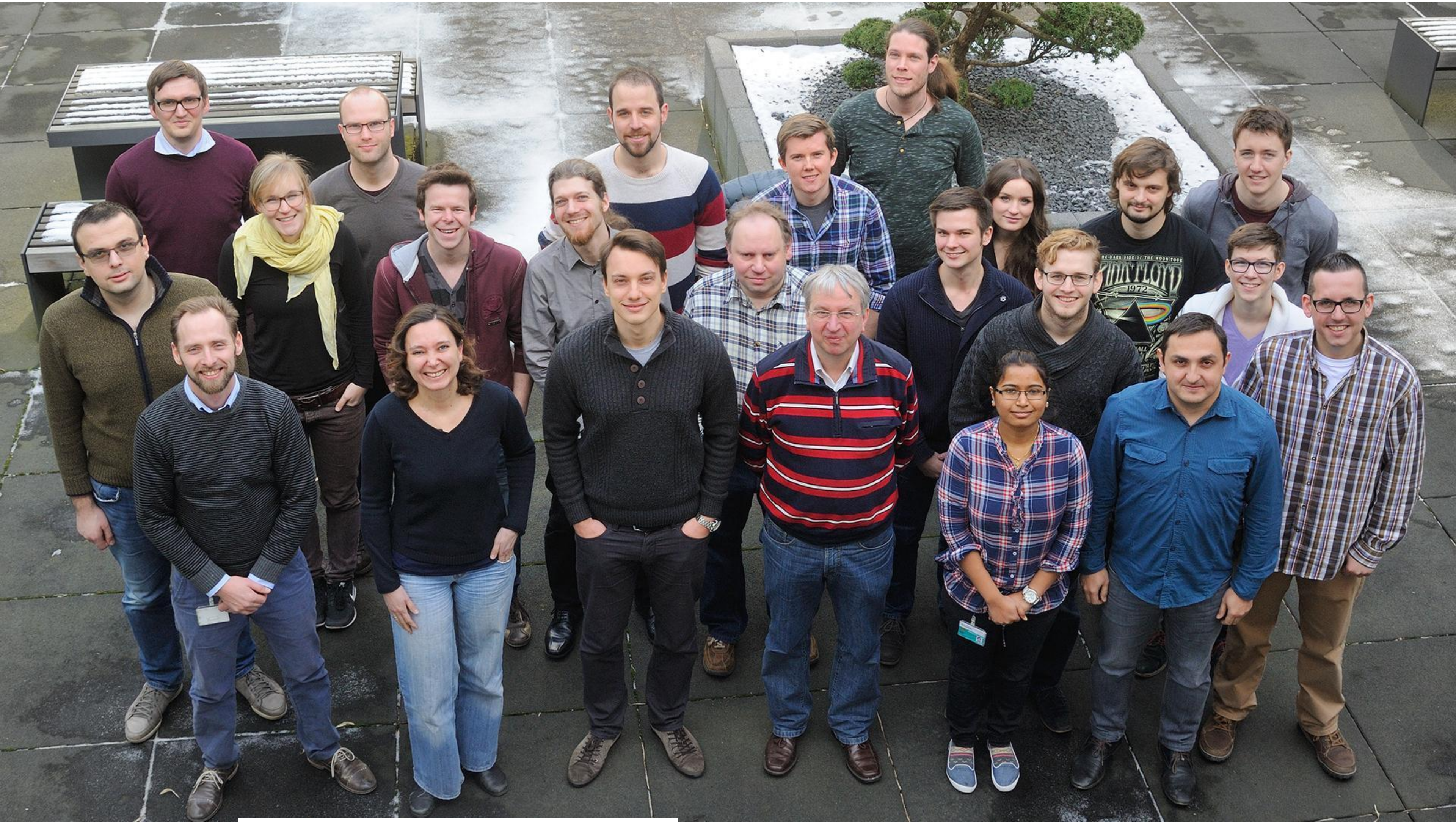
Thank you very much for your attention!



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